Historical Overview, Accelerator Examples and Applications

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Why Accelerators

Particle accelerators are devices producing beams of energetic particles such as ions and electrons which are employed for many different purposes.

This includes:

- **Ultra-precise Electron Microscopy**
- **Creation of New Particles**
- **High Brightness Photon Sources for Material Analysis and Modification, Spectrometry, … .**
- **Ion Implanters, for Surface Modification and for Sterilization and Polymerization**
- **Radiation Surgery and Therapy of Cancer**
- **…**

Ultra-Precise Electron Microscopy

Probing particles such as electrons and protons provided by particle accelerators are required for studies of atomic constituents. The associated de Broglie wavelength of a probing particle defines the minimum object size that can be resolved.

$$\lambda = h/p \text{, where}$$

$$h = 4 \times 10^{-15} \text{ eVs} \quad \text{(Planck's Constant)}$$

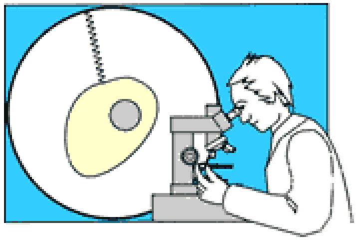
$$p \quad \text{(Particle Momentum)}$$

Resolving Smaller Objects Requires Higher Momentum Probe Particles

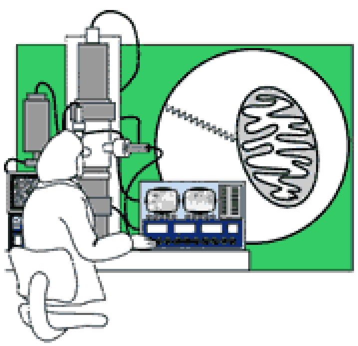
Example 1 : An electron with a 1 GeV/c momentum will have a de Broglie wavelength of 10^{-15}m (10^{-14} m ~ nucleus size, 10^{-15} m ~ proton size).

Example 2 : An electron with a 1 keV/c momentum will have a de Broglie wavelength of ~ 4.0 x 10^{-12} m. A photon with 1 keV energy has a wavelength $\lambda = ch/e$ ~ 1.2 x 10^{-9} m. This implies ~ 300 times better resolution and shows why electron microscopes have much better resolution than optical ones.

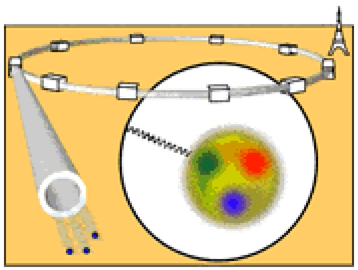
Ultra-Precise Electron Microscopy



The living cell is commonly studied by means of an optical microscope which receives scattered photons of visible light.



Sub-micron objects such as the constituents of a living cell are often investigated in electron microscopes where electrons, accelerated typically to a few hundred kilovolts, are used to hit the objects and scatter from them.



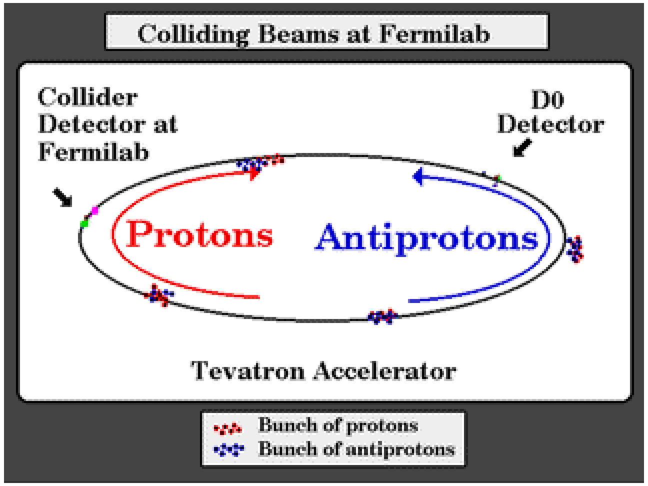
Quarks and leptons can be sensed down to distances of 10^{-18} meters by means of particles from giant accelerators with particle energies of ~100 GeV.

- Objects with dimensions down to the size of a living cell are investigated by optical microscopes and those down to atomic dimensions by electron microscopes.

- To penetrate the interiors of atoms and molecules, it is necessary to use radiation of a wavelength much smaller than atomic dimensions.

Creation of New Particles

Particles from accelerators colliding with target particles may lead to the creation of new particles, which acquire their mass from the collision energy according to the formula $E=mc^2$. It is thus by conversion to mass of excess kinetic energy in a collision that particles, antiparticles and exotic nuclei can be created.



Other Applications

Particle accelerators are not only unique as tools for the exploration of the subatomic world, but are also used in many different applications such as material analysis and modification and spectrometry especially in environmental science.

- **About half of the world's 15,000 accelerators are used as ion implanters, for surface modification and for sterilization and polymerization.**
- **The ionization arising when charged particles are stopped in matter is often utilized for example in radiation surgery and therapy of cancer. At hospitals about 5,000 electron accelerators are used for this purpose.**
- **Accelerators also produce radioactive elements that are used as tracers in medicine, biology and material science.**
- **Of a great and increasing importance in material science are ion and electron accelerators that produce abundant numbers of neutrons and photons (light sources) over a wide range of energies.**

What Are Accelerators Used For

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

History

Cathode Ray Tubes
Late 1800s

Multipole Gaps
Cockcroft Walton (1920)

Van Der Graff (1930)

Electrostatic Field Based

Time Varying Field Based

Time Varying Fields
Ising (1924) and Wideroe

Cyclotron
Lawrence (1930)

Synchrotron
Oliphant (1943)

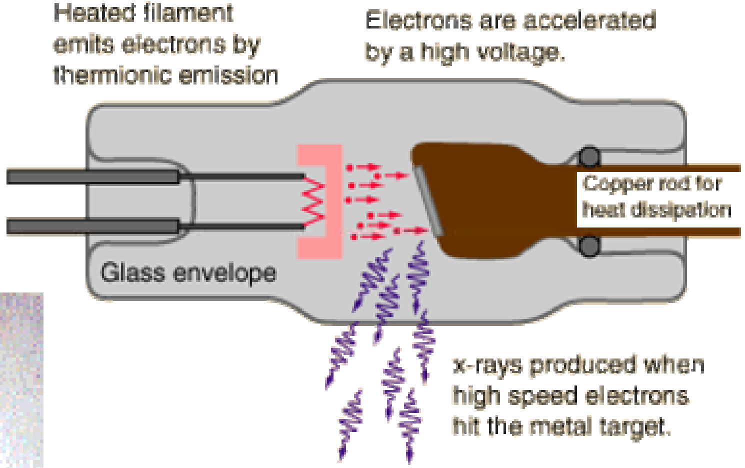
Synchrocyclotron and Betatron
McMillan and Veksler (1944)

Alvarez Linac
McMillan (1946)

Strong Focusing
Courant and Snyder (1952)

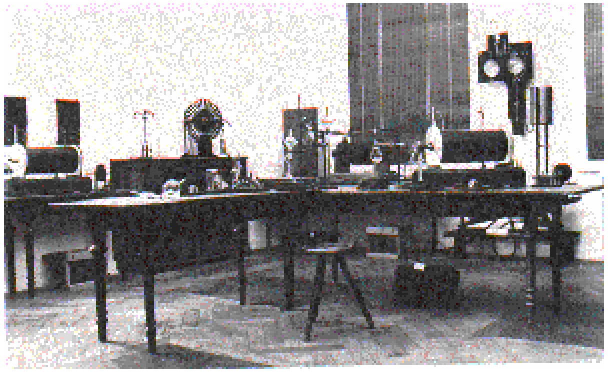
Discovery of X-Rays

Among the most important discovery for medicine.



From:
hyperphysics.phy-astr.gsu.edu

Wilhelm Conrad Röntgen (1845-1923)



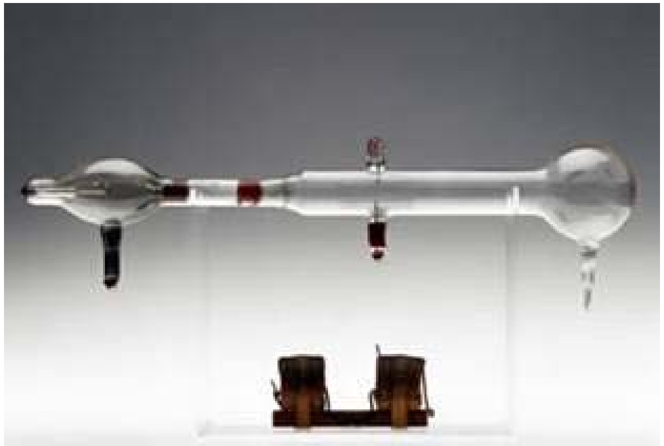
Crooke's Tube

Bertha Röntgen's Hand 8 Nov, 1895

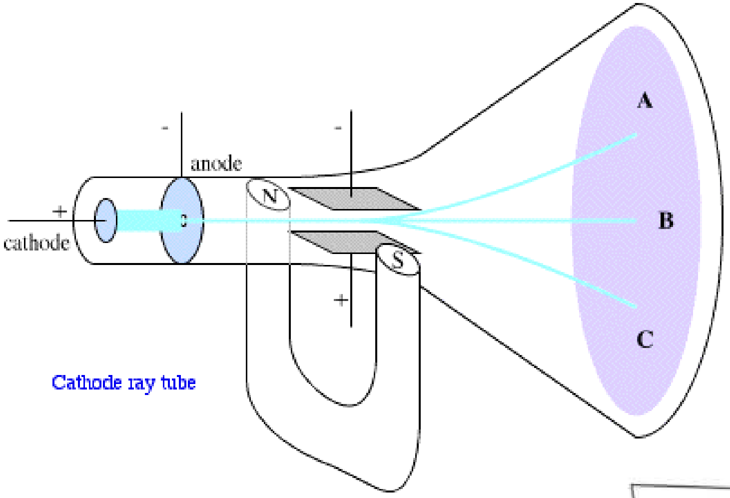
Modern radiograph of a hand

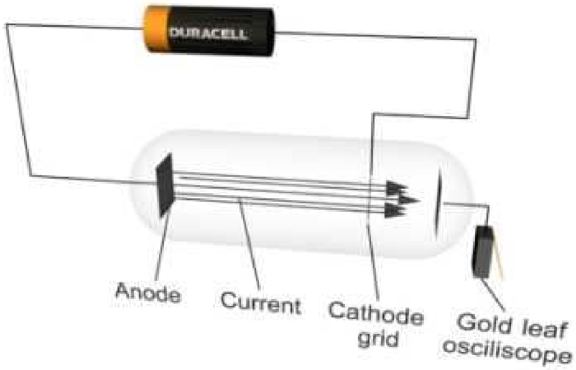
Discovery of Electron

In 1896 Joseph John Thomson investigated the nature of the cathode rays which were found to be charged and to have a precise charge-to-mass ratio. This discovery of the first elementary particle, the electron, marks the start of a new era, the electronic age.



Original vacuum tube used by J. J. Thomson





Beyond Cathode Ray Tubes

Cathode Ray Tubes are Single Gap Devices
→Small Energy (10s of KeV)

The existing different types of accelerators beyond Cathode Ray Tubes were invented during a time span of nearly four decades 1920 - 1960

Many of the items mentioned here will be discussed in more detail in Lecture 4.

Potential-Drop Accelerators

Potential Drop Accelerators Employ Electrostatic Fields

- The first high-voltage particle accelerator had a potential drop of the order of 100 kilovolts and was conceived by and named Cockcroft Walton Accelerator in 1920.

- The most common potential-drop accelerator in use today is named after its inventor, the American Robert Jemison Van de Graaff. Nowadays most van de Graaff accelerators are commercial devices and they are available with terminal voltages ranging between one and 25 million volts (MV)

In comparison the potential in clouds just before they are discharged by lightning is about 200 MV.

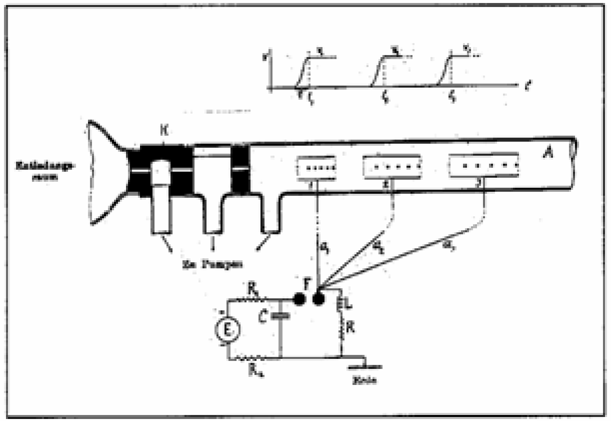
One of the biggest tandem accelerators was used for many years at Daresbury in the United Kingdom. Its acceleration tube, placed vertically, was 42 meters long and the centre terminal could hold a potential of up to 20 million volts. Photo: CCLRC

Time-varying voltage

The principle of repetitive acceleration conceived in the 1920s is an important milestone in the quest for higher and higher energies. According to this principle, acceleration is achieved by means of a time-varying voltage instead of a static voltage as used in e.g. van de Graaff accelerators.

- **In 1924, the Sweden G. Ising suggested that the maximum energy could be increased by replacing the single gap holding a DC voltage by placing along a straight line several hollow cylindrical electrodes holding pulsed voltages.**

- **The Norwegian Rolf Wideröe realized that, if the phase of the alternating voltage changed by 180 degrees during a particle's trip between gaps, the particle could gain energy in each gap. Based on this idea he built a three-stage accelerator for sodium ions.**

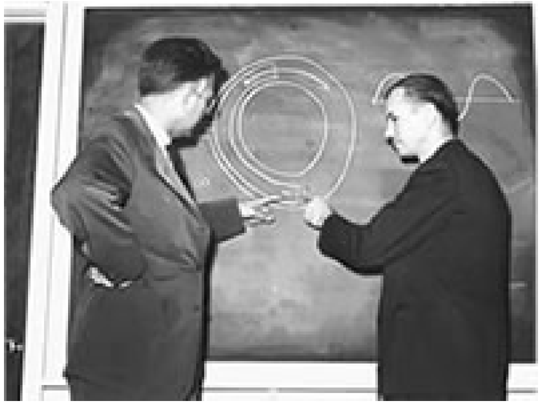


Ising's first suggestion for a linac

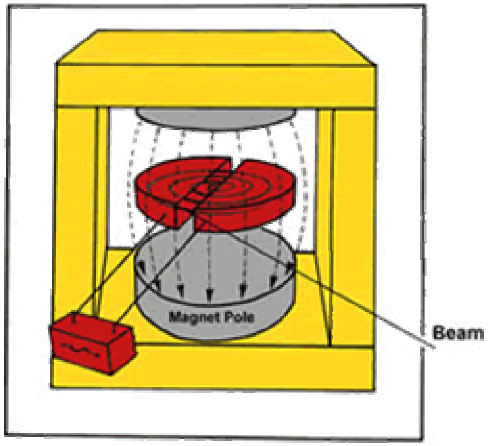
Rolf Wideroe

Cyclotron

The first circular accelerator of practical importance based on the principle of repetitive acceleration was the cyclotron, invented by Ernest Orlando Lawrence.



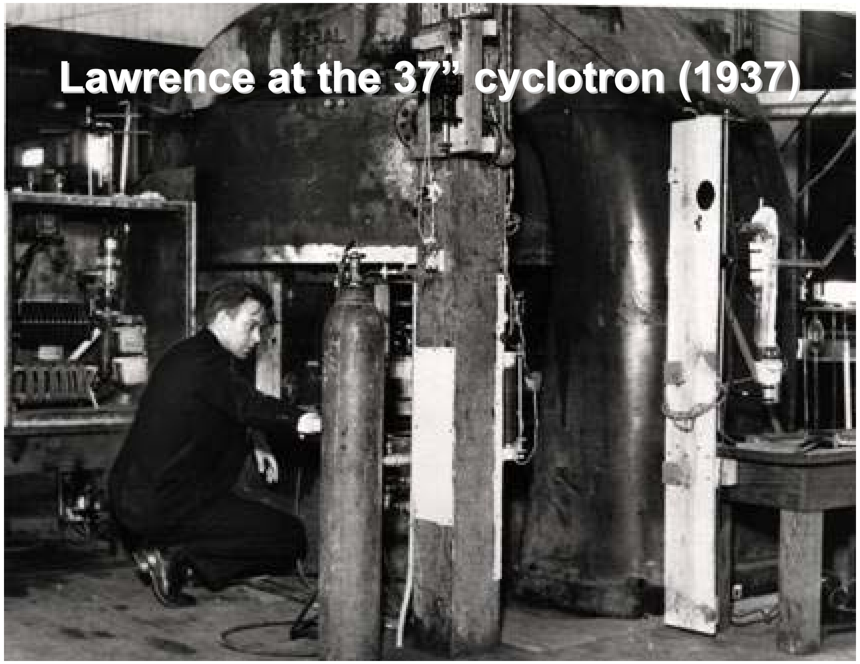
The inventor of the cyclotron, Ernest Orlando Lawrence (left), and his student Edwin Mattison McMillan



In a cyclotron, the charged particles circulate in a strong magnetic field and are accelerated by electric fields in one or more gaps. After having passed a gap, the particles move inside an electrode and are screened from the electric field. When the particles exit from the screened area and enter the next gap, the phase of the time-varying voltage has changed by 180 degrees so that the particles are again accelerated.

Cyclotron

The first cyclotron
4.5” diameter (1929).



Lawrence at the 37” cyclotron (1937)

- **In 1938 the first European cyclotron at Collège de France in Paris accelerated a deuteron beam up to 4 MeV and by hitting a target, an intense source of neutrons was produced.**

- **A serious problem with the early cyclotrons was the energy limit of <u>about 10 MeV</u> for the acceleration of protons. This limit depends on the slowing down of protons rotating in a constant magnetic field due to their relativistic increase of mass or equivalent total energy.**

Synchro-Cyclotron

To overcome the energy limitation of a cyclotron, the principle of phase stability was invented and proved in 1944/45. The inventors were Vladimir Losifovich Veksler and by Edwin Mattison McMillan, a former student of Lawrence, at the University of California in Berkeley.

The largest synchrocyclotron still in use is located in Gatchina outside St Petersburg and it accelerates protons to a kinetic energy of 1,000 MeV. The iron poles are 6 meters in diameter and the whole accelerator weighs 10,000 tons, a weight comparable to that of the Eiffel Tower. The energies attained correspond to that of a proton accelerated in a potential drop of one billion volts. It is used for nuclear physics experiments and medical applications.

They showed, independently of each other, that by adjusting the frequency of the applied voltage to the decreasing frequency of the rotating protons, it was possible to accelerate the protons to several hundred MeV.

Sector-Focusing Cyclotron

In the early 1960s, a new type of cyclotron, the sector-focusing cyclotron emerged. Iron sectors were introduced in the pole gap so that an azimuthal variation of the magnetic field was obtained. This azimuthal variation provides a strong vertical focusing on the circulating beam of ions and it is then not necessary to have the azimuthally averaged field to decrease with increasing radius as it has to do in the conventional cyclotron in order to maintain vertical focusing. Hence, the average magnetic field as a function of radius, can be increased so that the rotation frequency of the ion remains constant in spite of the increase of mass of the accelerating ion.

The separated sector cyclotron in Vancouver, provides 600 MeV negative hydrogen ions and it is the largest of all cyclotrons. The picture shows the gap inside which the ions are accelerated.

Sector-Focusing Cyclotron

Application of Cyclotrons with Heavy Ions:

- Sector focusing cyclotrons have been very useful for providing low-energy heavy ions.
- Using accelerated heavy ions, several new elements have been discovered first in Berkeley and Dubna and later in Darmstadt. The heaviest element so far discovered, element 110, was first found in Darmstadt and the discovery has been confirmed by the groups in Dubna and Berkeley. The research is still intense and element 112 has been claimed in Darmstadt, element 114 in Dubna.
- Since the maximum energy in a cyclotron is limited by the strength of the magnetic field and its radial extension, superconducting wire coils are now used instead of conventional copper coils around the iron poles to provide stronger fields.

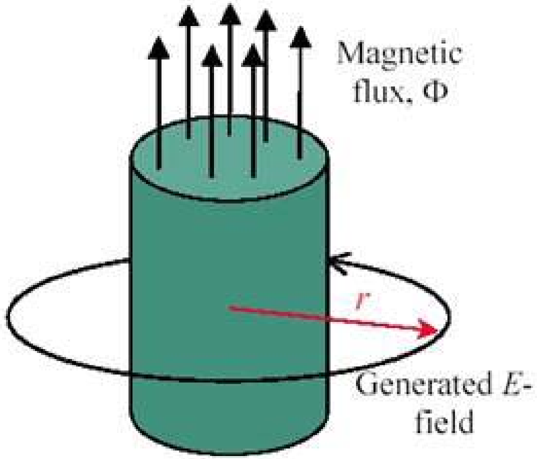
Betatron

- Principle investigated by **Wideröe** (1928) , **Steenbeck** (1935) and first one built by **Kernst** (1940) (energy of 20 MeV)
- Beta particles (=electrons) accelerated by rotational electric field generated by induction from time varying magnetic field $\mathbf{B}(t) = \mathbf{B_0} \sin(\omega t)$
- The magnetic flux $\Phi = \iint_A \mathbf{B}(r) \cdot d\mathbf{s} = \langle \mathbf{B} \rangle \pi r^2$
- From Faraday law of induction

$$2\pi r|E| = \oint \mathbf{E} \cdot d\mathbf{r} = -\iint_A \dot{\mathbf{B}}(r) \cdot d\mathbf{s} = \dot{\Phi} = -\pi r^2 \frac{d}{dt} \langle \dot{\mathbf{B}} \rangle$$

- Motion in uniform magnetic field imposes $|\mathbf{p}| = e\, r|\mathbf{B}|$
- Assuming a constant radius, the accelerating part of the Lorentz force $|\mathbf{F}| = -e|\mathbf{E}| = |\dot{\mathbf{p}}| = e\, r|\dot{\mathbf{B}}|$
- Equating the last equation with the one from Faraday's law we get **Wideröe's betatron condition**

$$\boxed{|\mathbf{B}(t)| = \frac{1}{2}\langle |\mathbf{B}(t)| \rangle + |\mathbf{B_0}|}$$



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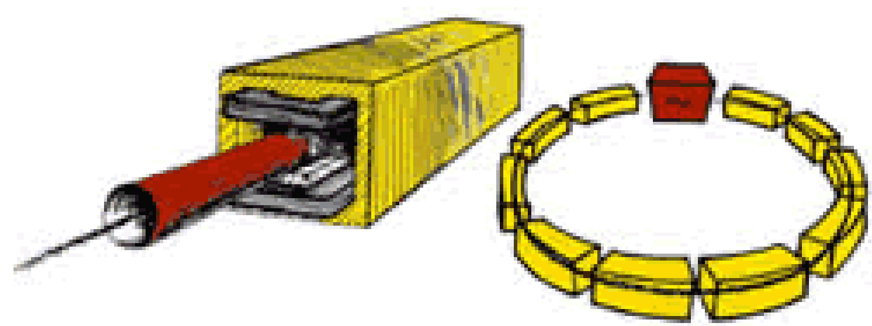
Synchrotron

The two other types of accelerators based on the principle of repetitive acceleration, the synchrotron and the linear accelerator, are important in elementary particle physics research, where highest possible particle energies are needed.

The synchrotron concept seems to have been first proposed in 1943 by the Australian physicist Mark Oliphant.



In synchrotrons, the particles are accelerated along a ring-shaped orbit and the magnetic fields, bending the particles, increase with time so that a constant orbit is maintained during the acceleration.

Weak-Focusing Synchrotrons

Weak Focusing

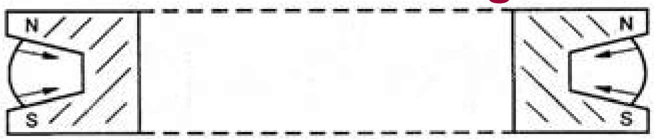


Figure 3.3. Cross section of weak focusing circular accelerator.

Cosmotron

The first synchrotrons were of the so called weak-focusing type. The vertical focusing of the circulating particles was achieved by sloping magnetic fields, from inwards to outwards radii. At any given moment in time, the average vertical magnetic field sensed during one particle revolution is larger for smaller radii of curvature than for larger ones.

- The first synchrotron of this type was the Cosmotron at the Brookhaven National Laboratory, Long Island. It started operation in 1952 and provided protons with energies up to 3 GeV.
- In the early 1960s, the world's highest energy weak-focusing synchrotron, the 12.5 GeV Zero Gradient Synchrotron (ZGS) started its operation at the Argonne National Laboratory near Chicago, USA.
- The Dubna synchrotron, the largest of them all with a radius of 28 meters and with a weight of the magnet iron of 36,000 tons

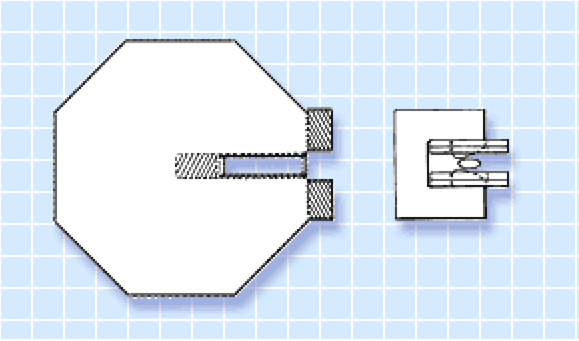
Strong-Focusing Synchrotrons

In 1952 Ernest D. Courant, Milton Stanley Livingston and Hartland S. Snyder, proposed a scheme for strong focusing of a circulating particle beam so that its size can be made smaller than that in a weak-focusing synchrotron.

- **In this scheme, the bending magnets are made to have alternating magnetic field gradients; after a magnet with an axial field component decreasing with increasing radius follows one with a component increasing with increasing radius and so on.**
- **Thanks to the strong focusing, the magnet apertures can be made smaller and therefore much less iron is needed than for a weak-focusing synchrotron of comparable energy.**
- **The first alternating-gradient synchrotron accelerated electrons to 1.5 GeV. It was built at Cornell University, Ithaca, N.Y. and was completed in 1954.**


Christofilos

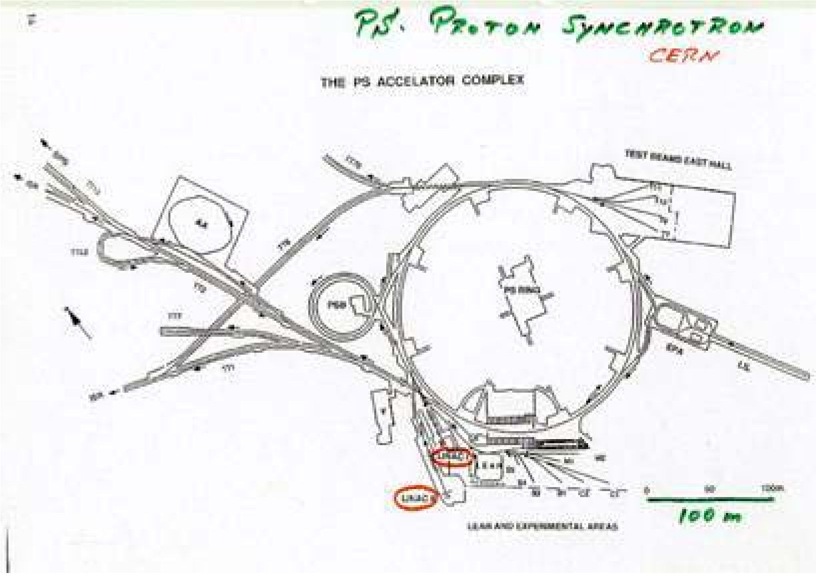

Courant Livingston Snyder



Size comparison between the Cosmotron's weak-focusing magnet (L) and the AGS alternating gradient focusing magnets

Strong-Focusing Synchrotrons

Soon after the invention of the principle of alternating-gradient focusing, the construction of two nearly identical very large synchrotrons, which are still in operation, started at the European CERN laboratory in Geneva and the Brookhaven National Laboratory on Long Island in New York. At CERN protons are accelerated to 28 GeV and at Brookhaven to 33 GeV. The CERN proton synchrotron (PS) started operation in 1959 and the Brookhaven Alternating Gradient Synchrotron (AGS) in 1960.



CERN PS

Brookhaven AGS

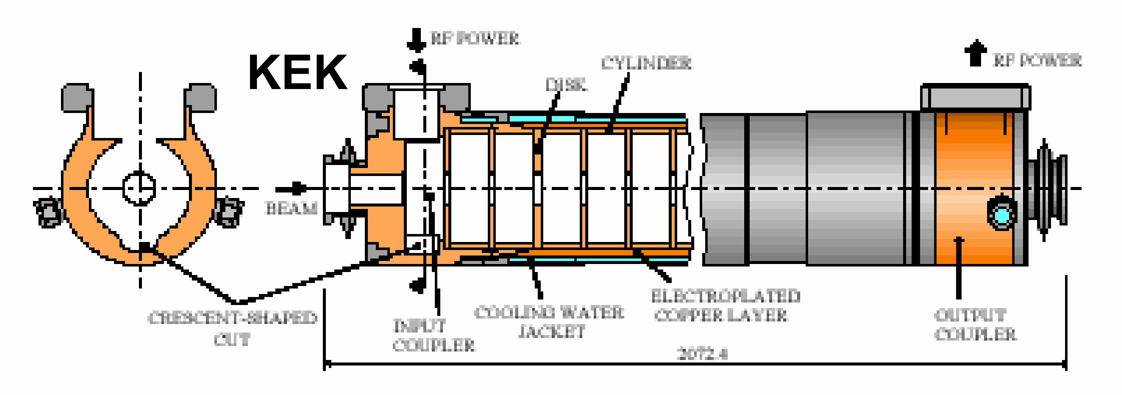
The Largest Synchrotron

Inside the 6.9 km long tunnel of the CERN 450 GeV super proton synchrotron. The blue magnets focus, and the red magnets bend the particles.

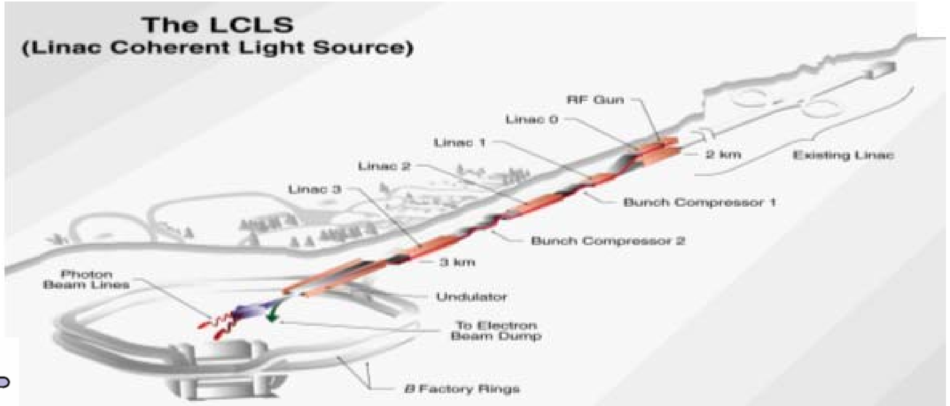
Aerial view of the CERN laboratory situated between Geneva airport and the Jura mountains. The circles indicate the locations of the SPS and LEP accelerators placed in underground tunnels. After the LEP accelerator has stopped operation at the end of the year 2000, it was dismounted and the large Hadron Collider (LHC) is currently being installed in the 27 km long tunnel.
Photo: CERN

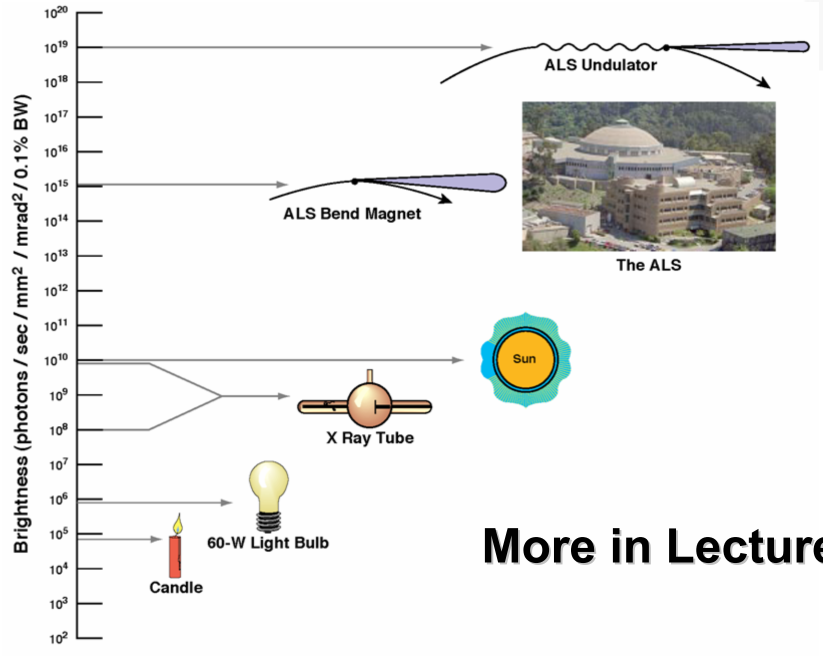
Linear Accelerators

- After Ising and Wideroe scheme, an improved version of a linear accelerator was conceived in 1946 by Luis Walter Alvarez who generated the radio frequency voltage differently; standing radio-frequency waves inside cylindrical cavities. These so called Alvarez structures are still used for ion and proton acceleration. Alvarez was awarded the 1968 Nobel Prize in Physics for his decisive contributions to elementary particle physics.
- A big boost to the development of linear accelerators came when Hansen and the Varian brothers (1937) developed the first klystron (frequencies up to 10 GHz) an efficient and high power source of radio frequency.
- In parallel, newer and more efficient RF structures were obtained by coupling together many pillbox-like cavities.
- Very high energy accelerators became a feasible reality and several machines where constructed.



Accelerator-Based Light Sources





More in Lecture 14!

Modern synchrotron light sources are accelerators optimized for the production of synchrotron radiation.

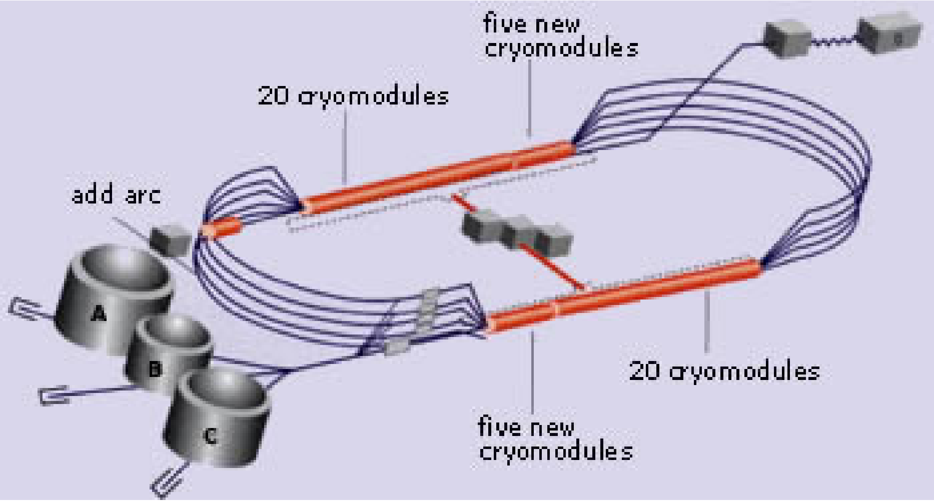
Colliding Beams

In the continuous race for higher energies, required in the search for undiscovered heavy particles and for the exploration of smaller distances, particle colliders have been found to be superior to other types of accelerator-based experiments (fixed target).

- The first electron-positron collider in operation was ADA in 1960 in Frascati. This little storage ring with a little more than 1 m diameter was conceived and designed by Bruno Toshek and operated at 250 MeV. ADA was the proof of principle that allowed to set the theoretical and experimental basis for the later construction of accelerators such as the LEP at CERN with almost 27 Km circumference.
- At the same time, pioneering work on how to collide two beams of electrons circulating in two synchrotrons was done in Novosibirsk at the Budker institute.
- The first collider to be used for experiments was the intersecting storage rings (ISR), used at CERN from 1971 to 1983.
- Several Nobel prizes were assigned for results obtained by accelerators (B. Richter and S. Ting 1976, C. Rubbia and S. van der Meer 1984)

Other Accelerators

Superconducting RF



The continuous electron beam facility (CEBAF) at the Jefferson Laboratory, Virginia, USA, accelerates electrons up to 6 GeV in a race-track microtron with a circumference of 1.4 km. Acceleration takes place in 338 hollow shells (cavities) placed in the straight sections inside cryomodules and the beam is bent 180 degrees in five different arcs. During the first revolution, the electrons move in the upper arcs, they descend successively and after five revolutions of acceleration they have reached the bottom arcs. Experiments are situated in three different halls, A, B and C. In the future, a new hall D will be added and the energy will be increased to 12 GeV.
Illustration: DOE/Jefferson Lab.

Other Accelerators

Cooler Storage Rings

- Cooling a circulating particle beam means reducing the momentum spreads and the transverse dimensions of the beam.
- Electron cooling was invented in Novosibirsk in the late 1970s and Electron cooling is useful for improving the quality of beams of protons, antiprotons and ions

Meson Factories

- During the 1960s, three accelerators were built to provide intense fluxes of beams of medium-energy, several hundred MeV, charged p-mesons.

Neutron Sources

- When a high-energy proton penetrates a target of heavy material such as lead, tungsten or uranium, numerous neutrons are knocked out. For example, one proton of 800 MeV stopped in a target of uranium gives rise to about 30 neutrons on the average.
- At present, the most powerful pulsed neutron source is located at the Rutherford Appleton Laboratory near Oxford, U.K., where a 70 MeV linear accelerator is the injector to a synchrotron that provides protons of 800 MeV with an intensity of 200 microamperes

Conclusion

Exponential growth of energy with time

- Increase of the energy by an order of magnitude every 6-10 years
- Every new idea evolves up to a point of saturation and than is replaced by another new idea

Energy is not the only interesting parameters where there has been phenomenal improvements

- Exponential growth in Brightness (for example) of 13 orders of magnetude in only 40 years!

With clever new ideas these advances will surely continue into the future!

Thanks

Wish to thank Y. Papaphilippou and N.Catalan-Lasheras for sharing the tranparencies that they used in the USPAS, Cornell University, Ithaca, NY 20th June – 1st July 2005

Wish to acknowledge the web based article Accelerators and Nobel Laureates by Sven Kullander which can be viewed at http://nobelprize.org/physics/articles/kullander/